

# Correlations Between Spectral Properties and Spin-Down Rate in Soft Gamma-Ray Repeaters and Anomalous X-ray Pulsars

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## ABSTRACT

Anomalous x-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are x-ray sources with unusual properties distinguishing them from both rotation-powered and most accretion-powered pulsars. Using archival *ASCA* data over the energy range 0.5 – 10.0 keV, we have studied the spectra of the persistent emission from these sources and their variation with spin-down rate. Using a single power law spectral model, we find that the overall hardness of the spectra increase with increasing spin-down rate, and therefore the spectral and spin-down mechanism are inextricably linked in these objects. In terms of the two-component blackbody plus power law spectral models, this correlation is seen as an increasing hardness of the high energy component with increasing spin-down rate, with the temperature of the low energy blackbody component remaining essentially constant. Also for the two component spectral model: the ratio of the 2 – 10 keV power law and bolometric blackbody luminosities gradually increases with the spin-down rate. We discuss these results in terms of the various theoretical models for SGRs and AXPs.

*Subject headings:* Stars: neutron – pulsars: individual (SGRs, AXPs)

## 1. Introduction

Soft gamma-ray repeaters (SGRs) and anomalous x-ray pulsars (AXPs) are a group of radio-quiet soft x-ray pulsars with spin periods in the range 5 – 12 s, rapid spin-down rates with no observed intervals of spin-up, and x-ray luminosities  $L_x \sim 10^{35}$  ergs s $^{-1}$ . Most of the SGRs and AXPs are associated with supernova remnants (e.g., Marsden et al. 2000 and references therein), implying that they are young neutron stars. The lack of Doppler shifts associated with binary orbital motion (Mereghetti, Israel, & Stella 1998; Kaspi, Chakrabarty, & Steinberger 1999) imply that SGRs and AXPs are not members of typical high mass binary systems, although systems with stellar companions of  $< 1M_\odot$  and Thorne-Żytkov systems (Ghosh, Angelini, & White 1997) are not constrained in most cases. Among the differences between SGRs and AXPs is the fact that SGRs occasionally emit multiple bursts of gamma-rays which have unique properties distinguishing them from other bursting sources (e.g., Hurley 2000 for a recent review), and the AXPs appear to have softer x-ray spectra than the persistent SGR emission (Stella, Israel, & Mereghetti 1998; Sonobe et al. 1994).

The theoretical models describing SGRs and AXPs can be divided into two categories based on the energy source powering the x-ray emission. The magnetar model (Duncan & Thompson 1992) postulates that the x-ray emission and rapid spin-down of SGRs and AXPs are due to an unusually strong magnetic field ( $B > 10^{14}$  G), which may decay on a  $10^3 - 10^4$  yr timescale and power the x-ray emission. In accretion-based models for SGRs and AXPs (Alpar 2000; Chatterjee, Hernquist & Narayan 2000), SGRs and AXPs are normal neutron stars, and their spin-down and x-ray luminosities are due to the accretion of material from a fossil disk formed from supernova ejecta. Here we focus on the spectral properties of the persistent emission from these sources, and how they relate to their spin-down rates. A more extensive analysis of the temporal and spectral properties of the SGRs and AXPs sample will be presented elsewhere.

## 2. Data Analysis & Results

*ASCA* consists of 4 co-aligned grazing incidence x-ray telescopes producing an angular resolution of  $\sim 1'$  over the energy range 0.5 – 10.0 keV (Tanaka, Inoue, & Holt 1994). We only used data from the Gas Imaging Spectrometers (GISs; Ohashi et al. 1996), because not all of the sources had usable Solid State Imaging Spectrometer data. The GISs are gas proportional scintillator detectors having moderate energy resolution ( $\Delta E/E \sim 8\%$  at 6 keV) and an effective field of view of  $40'$ . The data were screened using standard screening criteria and extracted using the XSELECT v2.0. The *ASCA* observations of all the SGRs and AXPs with known spin periods and period derivatives are listed in Table 1. Except for

three sources, the on-source spectra were taken from circular extraction regions of radius  $6'$  centered on each source, and background was accumulated from adjacent source-free regions. The AXP J1709-40 was  $> 10'$  off-axis and therefore highly distorted by the *ASCA* optics. For this source, on-source data were extracted from an elliptical extraction region elongated in an azimuthal direction around the optical axis. The AXPs 2259+59 and 1841-05 are situated amongst bright emission from their associated supernova remnants CTB 109 (Rho & Petre 1997) and Kes 73 (Gotthelf & Vasisht 1997; GV97), respectively. CTB 109 subtends almost half a degree and can be resolved by *ASCA*; we therefore extracted background data from an annular region  $6' - 7'$  from the AXP. Kes 73 is only  $4'$  in diameter and too small to be completely resolved by *ASCA*, so we followed GV97 and used background from a nearby *ASCA* observation of the Galactic Ridge, and modeled the SNR emission using a  $\sim 0.6$  keV thermal bremsstrahlung with Gaussian emission lines from Ne, Mg, Si, and S at  $\sim 0.9, 1.4, 1.8$ , and  $2.4$  respectively.

Before extraction for spectral analysis, all the *ASCA* data were searched for SGR-like bursts by binning the data on a 0.1 timescale and searching for bursts by eye. Bursts were only found in the September 1998 SGR 1900+14 data (see e.g. Murakami et al. 1999), and only time intervals without bursts from this data set were included in our analysis. All spectra were extracted from the event data using XSELECT, rebinned to 256 channels, and then grouped into bins containing at least 20 counts per bin to facilitate the proper fitting of the spectra using chi-squared. Standard GIS response matrices were used for the spectral fitting, and ancillary response files were generated using the *ASCA* tool ASCAARF. The  $0.5 - 10.0$  keV phase-averaged spectra of the SGRs and AXPs were fit to single power law and blackbody plus power law spectral models (modified by interstellar absorption) using XSPEC v11.0.1. The spectral parameters were averaged for sources with more than one observation.

The pulse period  $P$  determined for each object, and the assumed value of the period derivative  $\dot{P}$ , are listed in Table 1. Details of the pulsar timing analysis will be presented elsewhere, and the results given here are not sensitive to the exact values of the pulsar periods. Figure 1 shows the mean value of the single power law photon index for each object plotted as a function of the spin-down rate  $|\dot{\Omega}| = 2\pi\dot{P}/P^2$ , which is proportional to the spin-down torque. Generally the AXP spectra were not well-fit by the single power law model, and require the addition of a low energy spectral component. The single power law model did fit the SGR spectra well in general, but a notable exception is the April 1998 SGR 1900+14 data, which requires the two component model to adequately fit the spectrum (Woods et al. 1999). In spite of these uncertainties, the single power law photon index provides a good measure of the overall hardness of the spectrum, and Figure 1 indicates a distinct hardening of the SGR and AXP phase-averaged spectra with increasing spin-down rate. To investigate the spectral/spin-down rate correlation further, we have plotted the spectral parameters of the two component blackbody plus power law spectral model versus  $|\dot{\Omega}|$  in Figure 2. Shown are the blackbody temperature, power

law photon index, and  $L_{PL}/L_{BB}$ , which is defined as the ratio between the 2 – 10 keV power law and bolometric blackbody luminosities. The bolometric blackbody luminosity was calculated using  $L_{BB} = A\sigma T^4$ , where  $A$  is the emitting area,  $T$  is the blackbody temperature in Kelvins, and  $\sigma$  is the Stefan-Boltzman constant. The blackbody emitting area is obtained from the fitted normalization and an assumed distance, but the ratio  $L_{PL}/L_{BB}$  is independent of the distance. The blackbody temperatures are approximately constant, but with considerable scatter, as a function of  $|\dot{\Omega}|$ , but both the power law hardness and  $L_{PL}/L_{BB}$  increase with increasing spin-down torque.

### 3. Discussion

We have found correlations between the spectra and spin-down rates of SGRs and AXPs. In terms of the power law plus blackbody spectral model, the power law component hardens and the ratio between the 2 – 10 keV power law luminosity and the blackbody luminosity ( $L_{PL}/L_{BB}$ ) increases gradually as the spin-down rate increases. These observed correlations can be used to constrain the models for SGRs and AXPs. With respect to the accretion model, the spectra of known accretion-powered pulsars in binary systems (XRBs) are generally harder than the SGR and AXP spectra over the energy range 0.5 – 10.0 keV (White, Swank, & Holt 1983), and there is no known correlation between the spectral parameters and the spin-down rates of XRBs. If SGRs and AXPs are accretion-powered, then they clearly must have different physical parameters – such as accretion rate, magnetic field strength, and accretion geometry – than XRBs. Evolutionary scenarios of isolated neutron stars with supernova fallback disks (Chatterjee & Hernquist 2000) favor  $B \sim 10^{13}$  G for the the SGRs and AXPs, which are stronger than the typical fields of XRBs (Makashima et al. 1999, and references therein) and radio pulsars (e.g., Taylor, Manchester, & Lyne 1993). The magnetic field alone cannot explain both the spectral softness and the spectral/spin-down rate correlation in the SGRs and AXPs, however, because the spectra and the spin-down rates of XRBs depend on both the magnetic field  $B$  *and* the accretion rate  $\dot{M}$ . The spectra of accreting neutron stars have been calculated (e.g., Böttcher & Liang 2000) for stars with  $B \sim 10^{12}$  G, but it is unclear if these models can produce the correct spectral shape for the values of  $B$  and  $\dot{m}$  necessary to produce the rapid spin-down of SGRs and AXPs. These spectral models assume isotropic emission of seed photons from close to the neutron star surface and ignore the effects of beaming, which become significant for  $B > 10^{12}$  G. Since beaming reduces the Comptonization at the magnetospheric boundary layer where the hard emission would originate (M. Böttcher, private communication), more complete calculations are needed before the accretion models for SGRs and AXPs can be tested on the basis of their x-ray spectra.

In the magnetar model (Thompson & Duncan 1996), both thermal and non-thermal x-ray emission is expected from SGRs and AXPs, with the non-thermal power-law emission

originating from a hydromagnetic wind of particles in the magnetosphere accelerated by Alfvèn waves generated by the decaying magnetic field. The spin-down of magnetars is due to a combination of standard magnetic dipole radiation torque and torque from the wind (Harding, Contopoulos, & Kazanas 1999). Both of these torques increase strongly with magnetic field strength, and therefore the hardening of the power law spectral component with  $|\dot{\Omega}|$  implies a similar hardening of the underlying Alfvèn wave spectrum with increasing  $B$  if the SGRs and AXPs are magnetars. Unfortunately, we are unaware of any calculations of the non-thermal spectra of magnetars to compare with the data. The *luminosity* of the wind emission, however, should increase with magnetic field strength for a given wave amplitude (e.g.,  $L_A \propto B^2$ ; Thompson & Blaes 1998). This is qualitatively consistent with the increase of the  $L_{PL}/L_{BB}$  ratio with  $|\dot{\Omega}|$ , as there is no evidence that the thermal component of the SGRs and AXPs varies systematically with  $|\dot{\Omega}|$ .

A strong constraint on the magnetar model is provided by  $L_{PL}/L_{BB}$ , because the blackbody luminosity is expected to be a much stronger function of the magnetic field strength than the power law luminosity (e.g.,  $L_{BB} \propto B^{4.4}$ ; Thompson & Duncan 1996). Assuming the power law luminosity  $L_{PL} \propto L_A$ ,  $L_{PL}/L_{BB}$  should be a *decreasing* function of  $B$  and the spin-down rate. The opposite trend is observed in Figure 2, however, as  $L_{PL}/L_{BB}$  increases with  $|\dot{\Omega}|$  and the magnetic field strength. For consistency with the magnetar model, the power law component of the SGRs and AXPs must extend to energies much lower than the arbitrary 2 keV cutoff energy used to compute  $L_{pl}$ . If the power law in the two component spectral model is extrapolated to  $\sim 50$  eV, for example, then  $L_{PL}/L_{BB}$  becomes a decreasing function of  $|\dot{\Omega}|$  – in accordance with the magnetar model<sup>1</sup>. This implies that the SGR and AXP spectra must extend to the far-UV if they are magnetars. The spectral energy distributions of the sources must then break downward sharply for consistency with the optical flux measurements and upper limits (Hulleman, van Kerkwijk, & Kulkarni 2000; Kaplan et al. 2000). Observations of spectral breaks in the non-thermal persistent emission in the far-UV would be important evidence in support of the magnetar model, and additional multiwavelength observations of SGRs and AXPs are needed to constrain both the magnetar and accretion models for these sources.

#### 4. Summary

We have analyzed the spectra of SGRs and AXPs over the energy range 0.5 – 10.0 keV with *ASCA*, and have identified several interesting correlations between the spectra and the spin-down rates of these objects. For the single power law spectral model, the hardness

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<sup>1</sup>This ignores the dependence of the spin-down rate on  $\Omega$ , but since the sources have identical spin periods to within a factor of  $\sim 2$  this would be an insignificant correction

of the spectra increase with increasing spin-down rate. For the two component blackbody plus power law spectral model, the temperature of the blackbody shows no evidence of a systematic variation with spin-down rate, but the hardness of the high energy power law component and the ratio of the 2 – 10 keV power law luminosity to the blackbody luminosity both increase with increasing spin-down rate. These observations can be used to constrain the magnetar and accretion models for SGRs and AXPs. The increasing power law emission with spin-down rate is consistent with the magnetar model, but the emission from the power law must extend into the far-UV band for this model to be consistent with the x-ray data. In the context of the fossil disk model, the softness of the SGR and AXP spectra argue against accretion by analogy with the spectra of known neutron star accretors, but it is possible that high field accreting neutron stars with  $B \sim 10^{13}$  may still be consistent with the data. Calculations of the x-ray spectra of both magnetars and accretion-powered neutron stars with  $10^{13}$  G fields are needed to more adequately evaluate these models.

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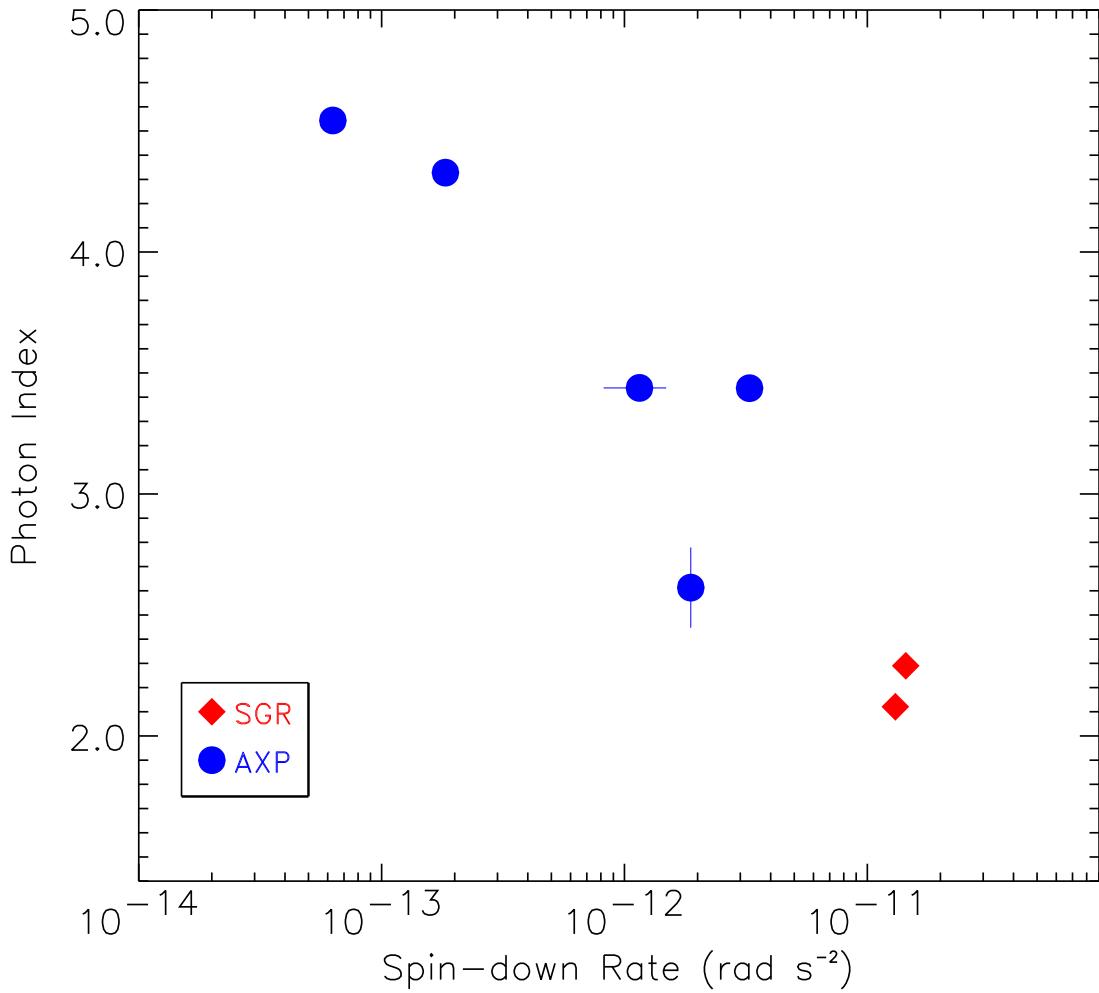


Fig. 1.— The variation of the single power law photon index versus spin-down rate  $|\dot{\Omega}|$  for each SGR and AXP, where the results for objects with more than one observation have been averaged. The photon index decreases (spectral hardness increases) with increasing spin-down rate.

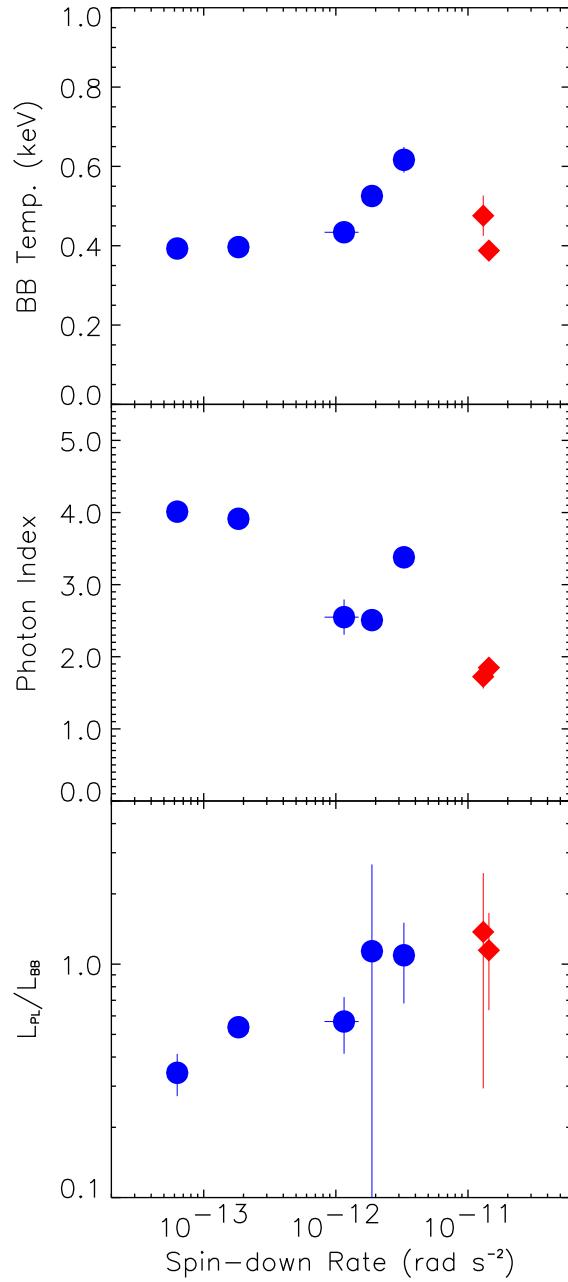


Fig. 2.— Same as Figure 1, except for the blackbody plus power law spectral model.  $L_{PL}/L_{BB}$  is the ratio between the 2.0 – 10.0 keV power law luminosity and the bolometric blackbody luminosity.

Table 1. SGR &amp; AXP Timing Parameters

Object	Start Date (mm/dd/yy)	$P^a$ (s)	$\dot{P}^b$ ( $10^{-12}$ s s $^{-1}$ )	Refs.
SGR 1900+14	04/30/98	5.158971(7)	$61.0 \pm 1.5$	1,12
SGR 1900+14	09/16/98	5.16025(2)	$61.0 \pm 1.5$	2,12
SGR 1806-20	10/10/93	7.468514(3)	$115.7 \pm 0.2$	3,13
SGR 1806-20	10/16/95	7.464445(3)	$115.7 \pm 0.2$	3,13
AXP 1048-59	03/03/94	6.446646(1)	$32.9 \pm 0.3$	4,5
AXP 1048-59	07/26/98	6.45082(1)	$16.7 \pm 0.2$	5
AXP 1841-05	10/11/93	11.76668(6)	$41.3 \pm 0.1$	6,7
AXP 1841-05	03/27/98	11.77243(7)	$41.3 \pm 0.1$	7
AXP 2259+59	05/30/93	6.97884(2)	$0.4883 \pm 0.0003$	8,13
AXP 2259+59	08/11/95	6.9788793(8)	$0.4883 \pm 0.0003$	13
AXP 0142+62	09/18/94	8.68794(7)	$2.2 \pm 0.2$	9
AXP 0142+62	08/21/98	8.68828(4)	$2.2 \pm 0.2$	5
AXP 1709-40	09/03/96	10.99758(6)	$22 \pm 6$	10,14

<sup>a</sup>Measured period ( $1\sigma$  error in last digit)<sup>b</sup>Assumed period derivative (from Refs.)

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